Keck Interferometer update

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ABSTRACT

The Keck Interferometer combines the two 10 m Keck telescopes for high sensitivity near-infrared fringe visibility measurements, nulling interferometry at 10 μm to measure the quantity of exozodiacal emission around nearby stars, and differential-phase measurements to detect "hot Jupiters" by their direct emission. First fringes with the interferometer were obtained in March 2001 using the two Kecks with their adaptive optics systems. Subsequent engineering work has been focused toward the visibility mode in the areas of system validation, and improving sensitivity, increasing automation, and adding functionality in preparation for nulling and differential phase. Recently four shared-risk teams were selected by NASA to participate in early science observations, and initial shared-risk science observations have begun.

Keywords: instrumentation: interferometers, instrumentation: adaptive optics, techniques: interferometric, nulling, differential phase

1. INTRODUCTION

1.1 Overview

The Keck Interferometer combines the two 10 m Keck telescopes in the following modes:

- *High sensitivity fringe visibility (V^2) measurements*. This mode combines the adaptive-optics (AO) corrected beams from the two Kecks for measurements of fringe amplitude in the near-infrared.
- *Infrared nulling at 10 μm*. Using a nulling beam combiner to suppress on-axis light, this mode will be used to measure the quantity of zodiacal dust around nearby stars for studies of planetary formation and for source selection for the Terrestrial Planet Finder mission.
- *Differential-phase interferometry*. Using a precision fringe detector and simultaneous multi-color observations of fringe position in the near infrared, this mode will be used to detect the fringe shift caused by hot companions to nearby stars.

At the present time, as the subsystems for nulling and differential phase are continuing their laboratory development, we are concentrating on the V^2 mode for its potential early science, and also because optimization of the V^2 mode addresses most of the system issues associated with the more advanced modes.

There is a proposal to add four to six 1.8-m outrigger telescopes to the Keck site, providing a range of baseline lengths of 30–135 m. With the outrigger telescopes, two additional modes would be provided:

- *High sensitivity imaging*. With four outrigger telescopes and two Kecks, 15 baselines would be available for synthetic aperture imaging; nine of these baselines would include at least one Keck, providing excellent sensitivity. Cophasing of the array on a nearby bright star allows increased sensitivity, and the large collecting area of the Kecks increases the cophasing limiting magnitude, and hence sky coverage.
- *Narrow-angle astrometry.* The outrigger telescopes would provide long near-orthogonal baselines for an astrometric search for planets to Uranus mass around nearby stars. Cophasing on the target star would be used to increase sensitivity for detection of an isoplanatic astrometric reference; operation over small fields with long baselines allows high accuracy through atmospheric turbulence.

The Keck Interferometer obtained first fringes in March 2001 using the two Kecks with their adaptive optics systems. Subsequent engineering work was focused toward the visibility mode in the areas of improving sensitivity, increasing automation, and adding functionality. Recently four NASA shared-risk teams were selected to participate in the early science phase of the project, and initial shared-risk observations have begun. Below, we discuss the first fringe activities last year (Sec. 2); followed by a status of the major instrument subsystems (Sec. 3). Section 4 discusses recent work, including several new subsystems. Section 5 concludes with current activities and near-term plans.

2. FIRST FRINGES

2.1 Siderostat Fringes

To optimize use of Keck time, plans to include two small siderostats to feed the interferometer were incorporated early in the project (Figure 1). They were installed in summer 2000 on the Keck site southeast of Keck II, providing a 20.4 m baseline, but with an output beam format that matches that provided by the Kecks.

The siderostat systems are similar to those in use at PTI[1]. Each siderostat uses a 50 cm flat, directing light to a fixed 40-cm telescope. The telescope is afocal, with a 10 cm output beam that is directed toward a fast steering mirror. The FSM directs the output beam through a window into beam transport optics at the basement level of the Keck facility. The beams from the siderostats intercept the Keck beam paths, and slide-in mirrors inject them into the remainder of the interferometer beam train in the same manner as light from the Kecks.

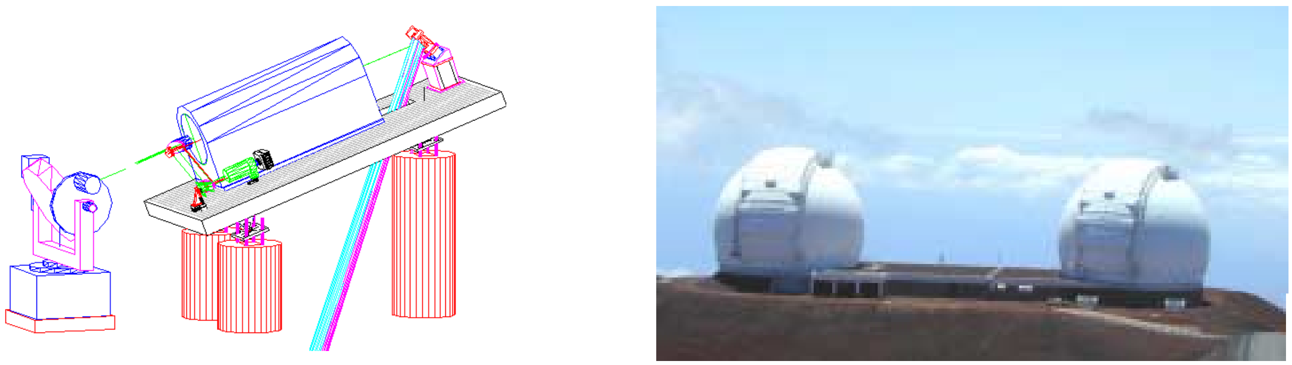

Figure 1 Left: Schematic of siderostat, telescope, and FSM; Right: Keck site, with siderostat shelters shown in the foreground of Keck II.

First siderostat fringes were obtained in February 2001, with H-band angle tracking and K-band synchronous fringe detection, validating operation of the interferometer subsystems. More detail on instrument configuration is given in Sec. 3.

2.2 Fringes with the two Kecks

First fringes with the two Kecks were obtained the following month, on March 12, the first night of a three-night run. Fringes were easily found, and the fringe quality was quite satisfactory for the first night of a new system. These observations used the two Kecks with their adaptive optics systems, and mark the first time AO-corrected beams have been combined interferometrically. Figure 2 shows delay and delay residuals from observations of 9 stars on the third night of the run. Correcting for intrinsic source visibility, the estimated system visibility for these stars was $V^2 \sim 0.75$; the delay residuals with respect to a best fit pointing model, assuming ideal pivots for the Kecks, were ~100 μm rms.

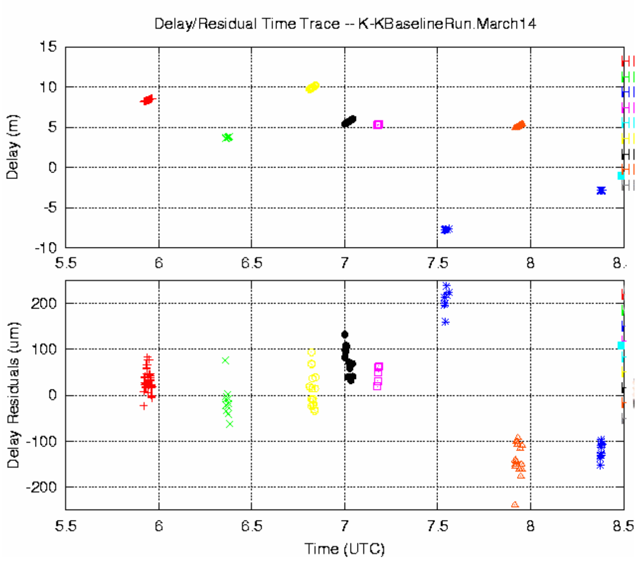

Figure 2 Delay and delay residuals for nine stars observed on March 14, 2001 during the first-fringe engineering run.

3. STATUS OF MAJOR SUBSYSTEMS

Below, we review and summarize the state of the various interferometer subsystems. Additional detail is available in the proceedings of the 2000 conference[2].

3.1 Telescopes and adaptive optics

As part of the interferometer project, an adaptive optics (AO) system was added to Keck I. This is a natural guide star system, and is essentially identical to the natural-guide-star part of the Keck II AO system[3]. First light with the Keck I AO system was in December 2000. It uses a Shack-Hartman wavefront sensor, a fast-readout CCD, and a 349-actuator deformable mirror. The corrected wavefront from the AO system is extracted in collimated space after the deformable mirror with a dichroic beamsplitter. The output beam diameter is 112 mm (inscribed circle), compressed 80.4:1 from the entrance pupil. A shutterable corner cube on the unused input to the beamsplitter can be used to back reflect laser light from the interferometer stimulus into the AO system's acquisition camera for alignment.

3.2 Dual-star module and coude path

The dual-star modules (DSMs) are located adjacent to the AO systems on the Nasmyth platforms of the two telescopes. They slide in on rails to kinematic locators (which on Keck II also accommodate NIRSPEC for (non-interferometric) use behind the AO system). For V^2 mode, the DSMs use flats to relay the output beam of the AO system to the telescope coude train; remote control of the DSM mirror closest to the AO system is used for co-boresighting of the interferometer and AO system optical axes.

The coude train uses flats to relay the beam to the basement level. For V^2 observations, only the primary (on-axis) coude path is used. Coude mirror M4 is on the DSM, M5 and M6 are on the telescope, and M7 is attached to the telescope pier beneath the azimuth axis. To maintain proper image rotation, both telescopes fold north after M7 to a second mirror, which then directs light through the coude tubes in the telescope piers to the beam combining lab.

3.3 Beam transport and basement lab

Figure 4 illustrates the light path through the basement for K2. As described elsewhere[2], modular cleanrooms partition the basement for cleanliness and environmental control. The beam injection and switching table directs the collimated beam from the telescope to the long delay lines (LDL). These are movable carts carrying flats which provide coarse (non-sidereal) delay, and which are repositioned only between observing programs. Currently only manually adjustable, they are in the process of having their motion control system installed. The LDLs and their tracks can be seen in Figure 3, photographed from the K1 side of the coude tunnel, with the beam injector table and K2 coude tube in the background. Slide-in mirrors on the beam injector table are used to switch between the Kecks and the siderostats (which feed in from the top in Figure 4). The LDLs reflect light back to the beam injector table, and the light is then directed toward the fast delay lines.

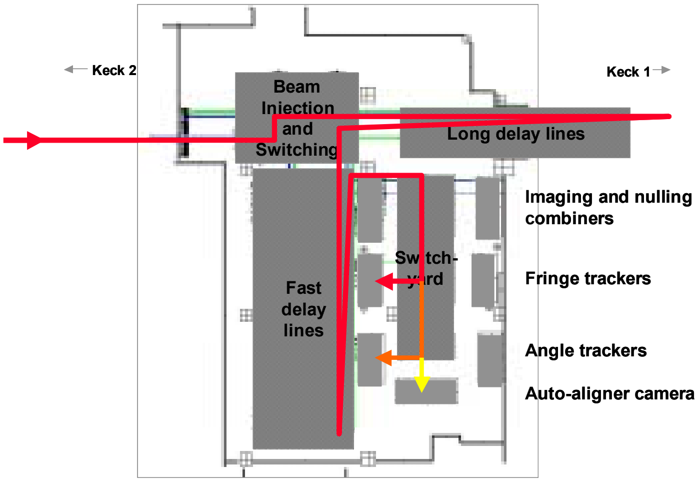

Figure 4 Light flow through the basement for K2.

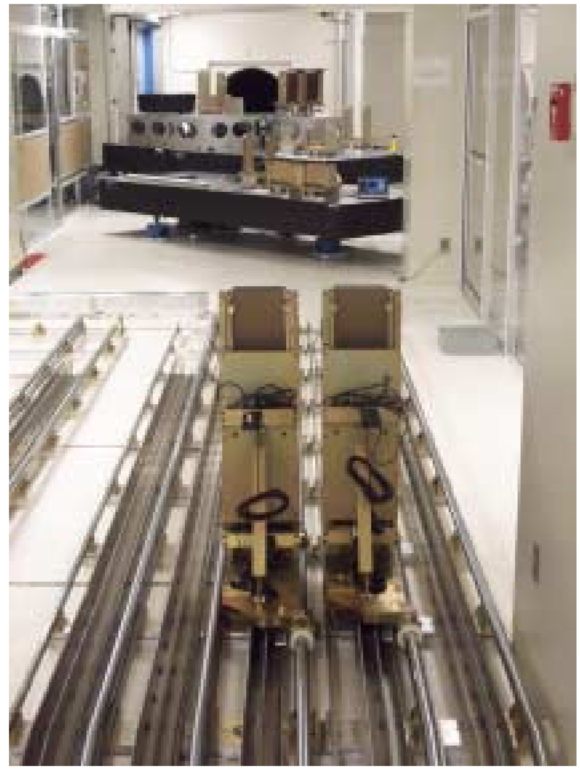

Figure 3 Long delay lines.

3.4 Fast delay lines

The fast delay lines (FDLs) run on rails as indicated in Figure 4; the door to the FDL area is seen in the upper left of Figure 3. The usable physical travel of the FDLs is 7.5 m, such that two delay lines provide +/- 15 m of sidereal delay about the delay center established by the position of the LDLs. Laser metrology monitors the position of the FDLs with a delay resolution of 1.2 nm; the FDL control algorithm is similar to that used at PTI. Under closed loop control, the FDLs achieve a jitter of 10's of nm while tracking at sidereal rates. They can accept targets from the fringe tracker, supplemental laser metrology, and other sources, and provide the fringe scanning needed by the fringe tracker. After exit from the fast delay lines, the light is compressed 4:1 for beam combination.

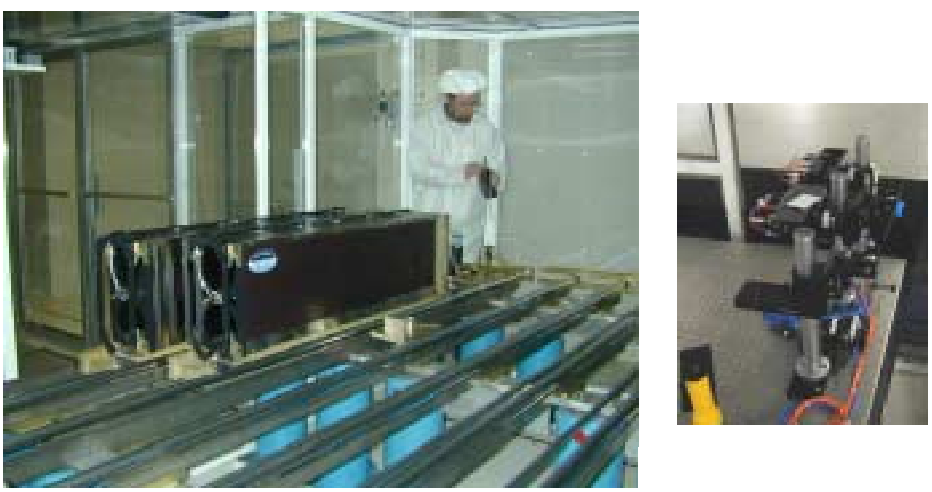

Figure 5 Fast Delay Lines and fiber-fed metrology launchers.

3.5 Fringe trackers and angle trackers

The fringe detector uses a HAWAII near-IR infrared array in a fast readout mode for fringe detection. It is fiber fed from free-space combination optics, and is described in detail elsewhere in this conference[4]. It is used for all of the modes of the interferometer. The fringe tracker implements a 4-bin synchronous fringe demodulation algorithm on white-light and spectrometer channels at frame rates as fast as 1000 Hz. The integrated phase feeds the FDL to track out atmospheric turbulence, and an outer-loop group-delay tracker resolves 2π ambiguities in the track point.

The angle tracker similarly uses a HAWAII array; multiplex optics produce J- or H-band images from the two Kecks onto 16x16 subarrays which are read out at rates up to 100 Hz. Centroiding is used for star acquisition in the subarray, while a 4x4 quad cell is used for fine tracking. The angle tracker implements an integral controller for tip/tilt mirrors in the switchyard that are used for high-speed control; low-bandwidth offloads are passed to the AO system.

The fringe and angle trackers are fed by dichroics: K band and most of H is directed to the fringe tracker; H band leakage, J, and most of I, go to the angle tracker; visible light passes through to the autoalignment camera.

3.7 RTC system

The Keck Interferometer real-time system is described in detail elsewhere in this conference[5]. Very briefly, the real-time portion uses VMEbus, PowerPCs, and VxWorks. High-rate applications are built using a distributed real-time control system toolkit that address commanding, configuration, telemetry, IPC, etc., described elsewhere at this meeting[6], and which is used on other interferometer projects at JPL. Lower-rate applications use EPICS, which is widely used at Keck Observatory, to implement similar functions. The non real-time portion runs typically on Unix workstations, and includes user interfaces (JAVA and Tcl/Tk (also described elsewhere at this meeting[7])), configuration databases and tools, and observing sequencers.

3.8 ISC tools

During the development phase of the Keck Interferometer, the Interferometry Science Center provides, among other services, the data archiving, indexing, and extraction tools[8]. The interferometer can produce a prodigious amount of data of various types per night, all of which is stored in real-time by an archiver program. The indexing and extraction tools have evolved since first fringes and provide simple command-line data access to the archive for simple diagnostics; the programming API provides more powerful access for additional services, including quick-look visualization, and data post processing. Finally, the ISC has provided a number of observation planning and calibration tools for science and engineering users.

4. RECENT ACTIVITIES

Recent work since first fringes has been focused on system validation, and improving the V^2 mode with respect to performance, functionality, and automation.

4.1 System validation

One of our preliminary system validation tests was observation of a known target. Figure 6 shows data from the spectroscopic binary system 3 Boo (HD120064), for which a good orbit has been determined from PTI. In the graph, the dotted line is the predicted time evolution of V^2; the lower set of points are estimates of the system visibility from observation of calibrators; the upper set of points are the calibrated visibilities. Consistency of the data to the prediction is within a few percent.

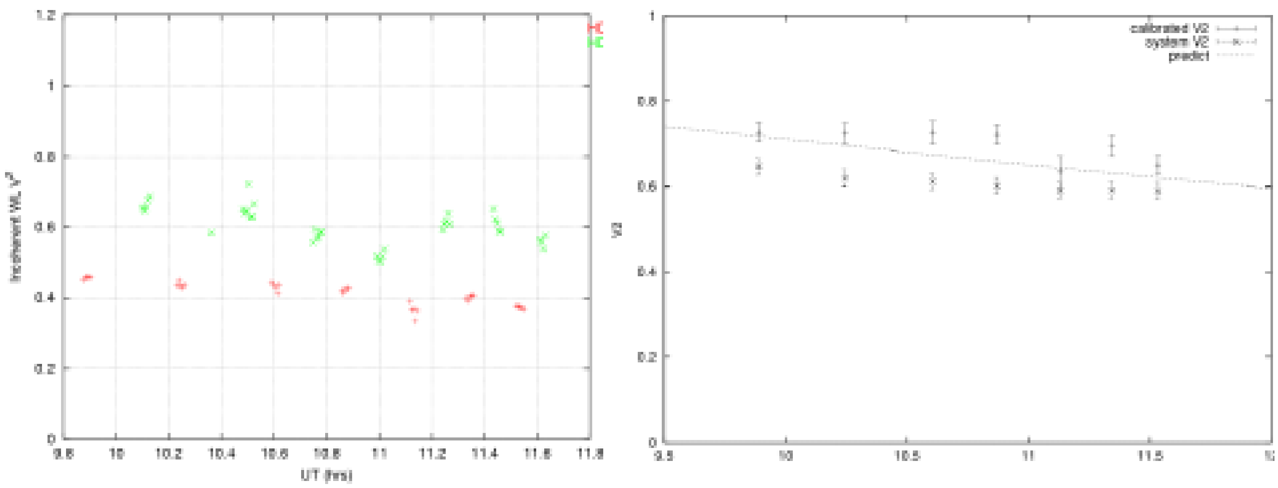

Figure 6 Left: target and calibrator visibility vs. time from April 27, 2002; Right: calibrated visibilities vs. prediction.

4.2 Performance improvements

To date, we have used short integration times on the starlight sensors to mitigate the effects of residual OPD and tilt vibrations in the optical system, limiting sensitivity. To exploit the excellent Mauna Kea seeing and to provide the very high performance levels needed for the upcoming high-precision modes – nulling and differential phase – we have worked to quiet the interferometer beam train. The work has included survey and measurement of the facility and facility disturbance sources, and isolation or suppression of the largest contributors, which is described elsewhere at this meeting[9]. In parallel with this activity, we have worked to essentially increase the bandwidth of our active control systems to suppress whatever remains after source mitigation, moving up the implementation schedule of systems planned for, or allowed for in design of, the high precision modes.

End-to-end laser metrology

First fringes used just local metrology of the fast delay lines with end-to-end pathlength control provided by measurement of the fringe phase. However, even with fast frame times, it's difficult to get OPD suppression using starlight at rates above ~50 Hz, and hence we moved up the implementation of our end-to-end metrology system. As implemented for V^2 observations, separate heterodyne metrology beams are injected backwards into each interferometer arm via Rugate filters (a dichroic beamsplitter reflective only at the laser line) near the fringe tracker dichroics. The measured paths terminate at corner cubes on the dual-star modules mounted behind the first DSM mirror; that mirror has a through hole (approximately the size of the projected telescope secondary obscuration) to pass the laser metrology. The real-time control system uses what is effectively a crossover to combine the local and end-to-end metrology to form a composite error signal for the fast delay lines. In this way the local metrology is used to maintain the dc position of the delay lines, while the end-to-end metrology is used monitor ac vibrations. With a 4 kHz sample rate, high bandwidth broadband suppression can be provided, with additional suppression at specific narrow frequencies.

Telescope feedforward

In addition to vibrations of the internal optical train, motion of the telescope optics, and motion of the AO and DSM benches – essentially everything between the end point of the laser metrology system on the DSM and the sky – also affect the total optical path as seen by starlight. Thus we have instrumented each telescope with 15 micro-g accelerometers: 6 are mounted to the primary (on 3 segments), 3 each to the secondary and tertiary, 1 each to the input and output of the AO bench, and 1 to the DSM bench. The accelerometers are used both for diagnostics as well as for real-time compensation. For the latter, a high-speed loop digitizes and filters the accelerometer signals to provide an estimate of the total starlight OPD contributed by rigid-body motion at the monitored points at frequencies above a few Hz. The negative of this OPD estimate is provided as an additional FDL target, canceling the OPD contribution as seen by starlight. Broadband suppression of at least 10X should be available from 8-40 Hz.

Tip-tilt metrology

As with the case of the fringe tracker, the control bandwidths achievable using only starlight sensed by the angle tracker are not adequate to provide a high degree of tilt suppression. To address this, an auxiliary tip/tilt system was installed. The beacon for this is the interferometer boresight laser on the fringe-tracker table, which back illuminates the optical train, producing an image on a position-sensitive silicon photodetector that is fed by a simple camera relay located on the DSM in the projected shadow of the telescope secondary. The controller filters the measured tilt error to drive fast tip/tilt mirrors which were installed in the interferometer basement in the 2.5 cm collimated space, and provides a few hundred Hz closed-loop bandwidth. The tip-tilt metrology works with the angle tracker, which also controls these same mirrors (previously, the angle tracker commanded the AO system directly, but at a much lower update rate); low bandwidth desaturation to the AO system keeps the mirrors near the center of their ranges.

Other performance areas

Additional performance improvements include the installation of windows and dichroics with optimized coatings for better starlight throughput; improvements to the internal throughput of the fringe tracker dewar; reductions in read noise for both the fringe-tracker and star-tracker electronics, and installation of laser-block filters for the AO system.

4.3 New functionality

In addition to the three new active systems described above, we have recently commissioned a differential atmospheric refraction corrector to correct for the different wavelengths of the fringe tracker and the angle tracker. It is implemented with a pair of Risley prisms at the input to the angle tracker dewar. Previously we had been running the angle tracker at H band, and restricting zenith angle, to minimize uncompensated refraction between the angle tracker and fringe tracker. However, H-band transmission to the angle tracker is poor (by design – most H-band light is reserved for the fringe tracker); with the corrector, we can move the angle-tracker to J-band – its design band – which provides significantly more flux, and also eliminates the zenith angle restriction, providing increased sky coverage.

A number of enhancements were made to the software for the real-time systems for improved operation on the sky, and for ease of use. The RTC toolkit was also updated, provided improved telemetry performance, and more convenient configuration control. The user interfaces underwent the biggest changes, with a new implementation that is very flexible and with much higher performance.

4.4 Automation

Automation is required with a complex instrument like an interferometer to maintain high science throughput, as well as to simplify, and reduce errors in performing, routine operations like alignment and calibration.

Figure 7 Two transport optics with their alignment targets

Beam train alignment and remote controls

One main area for automation is beam-train alignment; the interferometer's autoalignment system is undergoing testing, and is discussed elsewhere in this conference[10]. The system uses the back-end autoalignment camera – basically just a visible CCD – to measure the centroids of targets at various locations in the optical train. The targets are LEDs that flip into the center of the beam path in front of a mirror. The alignment process works backward from the beam combiner, centering on each target by actuating the preceding mirror. The flip-in targets on two of the custom transport-optic mounts are shown in Figure 7.

In addition to the autoalignment system, a large number of remote controls have been added to the interferometer over the past year, controlling hatches, mirrors, shutters, stimuli, and retroreflectors, which have simplified test and calibration. Finally, an autofill system is in the process of being tested to automate the filling of the cryogenic dewars.

Sequencing

Recent observing runs have included initial testing of the interferometer and telescope sequencers. The interferometer sequencer sequences a single scan, including collection of fringe data and all required calibrations (background, etc.), shuttering and commanding subsystems as required. The telescope sequencer provides coordinated slew commands to each telescope and AO system, starts the object acquisition process, and will ultimately be integrated with the observing list sequencer. More detail on sequencing and remote controls is discussed elsewhere[5].

5. CURRENT ACTIVITIES AND NEAR-TERM PLANS

5.1 Summit activities

In addition to further work with respect to performance, functionality, and automation of the V^2 mode, the current activities and near-term plans include:

Shared risk science observations

From proposals submitted in response to a NASA Research Announcement, four teams were selected in October 2001 to participate in shared risk science observations with the Keck Interferometer. During development phase, a goal of the project is to allocate a fraction of each engineering run (there are typically 4 engineering runs per 6-month scheduled semester) to shared-risk science. The first shared-risk data were taken in June 2002.

System characterization

As the system modifications described above are commissioned, detailed system characterization becomes important to model performance for science planning, and to understand the errors in collected science data. Part of the characterization can be accomplished as part of shared risk observations, by, for example, including cross calibration sources. Other characterization will require explicit experiments during the pure engineering time.

V^2 Observing mode handover

While JPL, WMKO, and ISC are partners in the instrument and system development, upon project completion, operation, maintenance, future development, and science operations will be carried out by WMKO and ISC. To ease this transition, the current plan calls for a series of intermediate handovers[11]. These include mode handovers, where the process addresses the operation of the interferometer for science and engineering observing, and subsystem handovers, where the process addresses the transference of maintenance and future development of a subsystem to WMKO. The first handover in the process will be the V^2 observing-mode handover.

Preparation for the high precision modes

The nulling and differential-phase modes require infrastructure changes to accommodate their particular requirements, and these additions will be made prior to their delivery.

5.2 Nulling and differential-phase laboratory development

Laboratory development of the two Keck high precision modes, nulling and differential phase, continues at JPL.

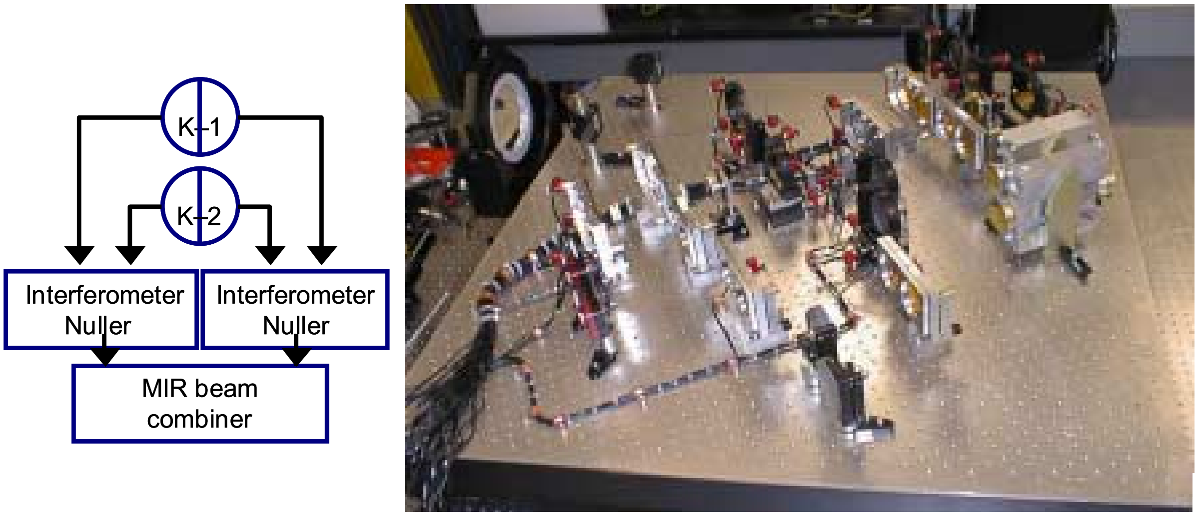

Figure 8 Schematic of nulling architecture, and nulling breadboard at JPL.

Nulling development is discussed in detail elsewhere at this meeting[12]. The nulling architecture uses a pair of modified Mach-Zehnder interferometers to separately null the left halves of the two Kecks and the right halves of the two Kecks, as illustrated in Figure 8. These nulled outputs are then combined in a conventional fringe-scanning Michelson combiner. Good performance has been measured in laboratory tests with thermal sources. Figure 8 also shows a photo of the nulling breadboard.

Differential phase development is similarly proceeding at JPL. The differential phase architecture uses multi-color fringe position measurements across K and L; a dedicated vacuum delay line, in production, is used for dispersion control. A precision path-length modulator, monitored with separate laser metrology with 10's of picometers short-term accuracy, works in coordination with synchronous demodulation of the fringe phase to provide a highly accurate fringe engine. Figure 9 shows the pathlength modulator under test, with two picometer laser gauges which are being cross-compared for consistency. Details on the gauges and modulator are presented elsewhere at this conference[13].

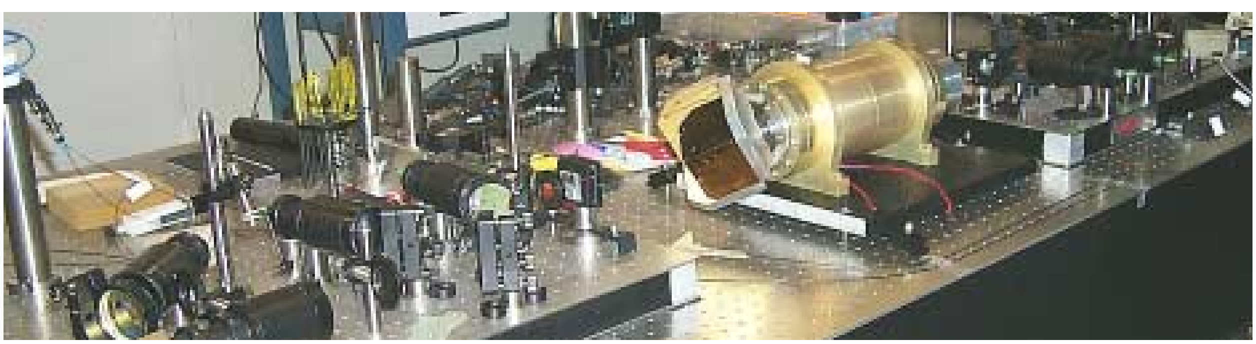

Figure 9 Precision path-length modulator for differential phase, and two picometer gauges under test.

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